Jet Propulsion Laboratory
California Institute of Technology

A Flight-Traceable Cryogenic Thermal System for Use in a Sample-Capture Flux-Pinned Interface

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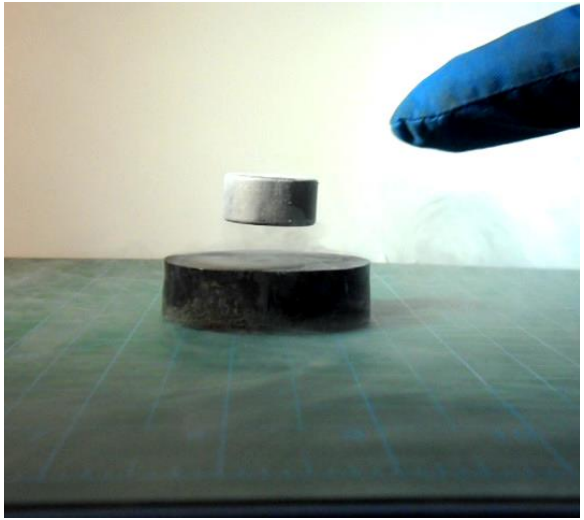
March 7, 2019

Problem Introduction

Flux Pinned Interfaces (FPIs)

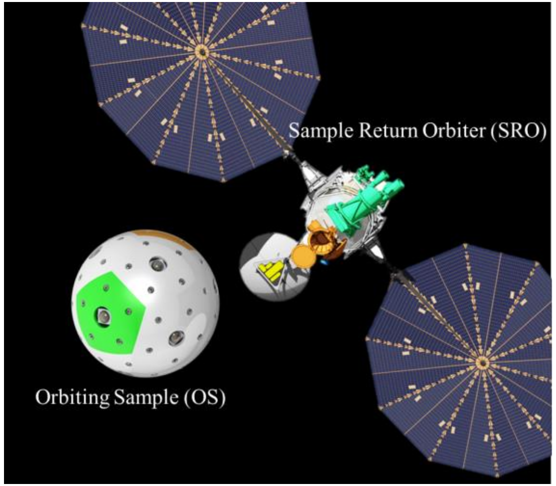
- A promising technology to manage the dynamic behavior of close-proximity spacecraft
  - Provide passively stable equilibrium
- Flux pinning occurs when a Type-II superconducting material is cooled to below its critical temperature in the presence of an external magnetic field
  - Typical critical temperature: ~77 K
    - Makes measuring dynamic interaction challenging
- In need of technology development
  - Characterize dynamic interaction
  - Flight-like thermal subsystem

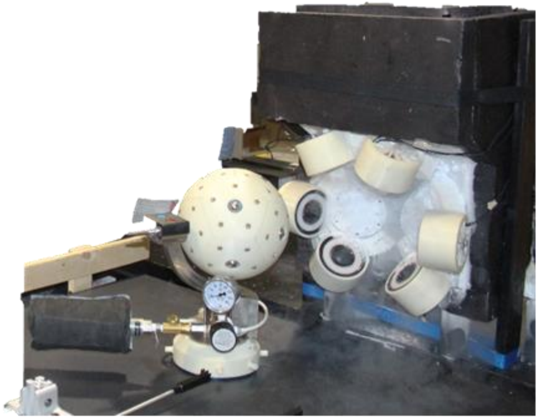


Problem Introduction

Testbeds for Measuring Dynamics

- Potential application: Sample capture for Mars sample return
  - Sample return orbiter
    - Orbiting spacecraft containing superconductors
  - Orbiting sample
    - Sphere containing planetary samples with permanent magnets on perimeter
- Thermal subsystem needs for testbed:
  - No condensation on surfaces
  - Operational times on the order of many hours
  - Fine temperature control of superconductor temperature
    - Stability and accuracy important below 88 K
  - Minimal spacing between superconductor and magnets with precision alignment
  - Minimal use of ferromagnetic material in system
    - Limits external forces and torques

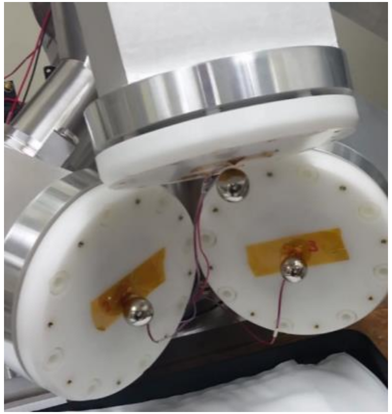


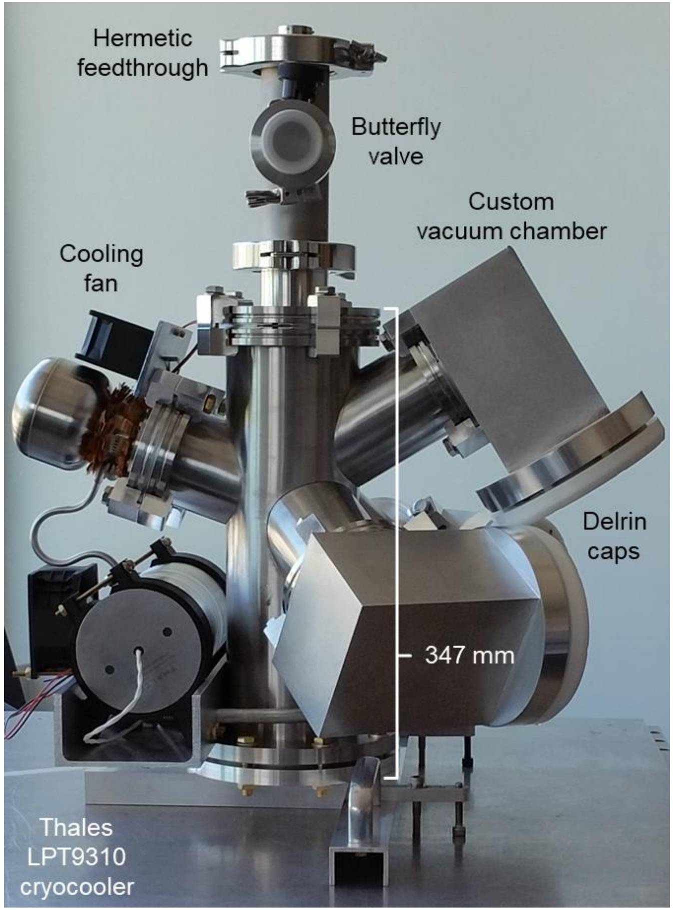


Solution

Device Description

- Modular thermal vacuum system
  - Able to be used in multiple testbeds
- Non-consumable cooling source
  - Cryocooler with flight-heritage
    - ECOSTRESS
  - Thales LPT9310
    - 7.0 kg
- Meets thermal needs
  - Room temperature exterior
  - Indefinite operation
  - Closed loop temp control
  - Aluminum near FPI

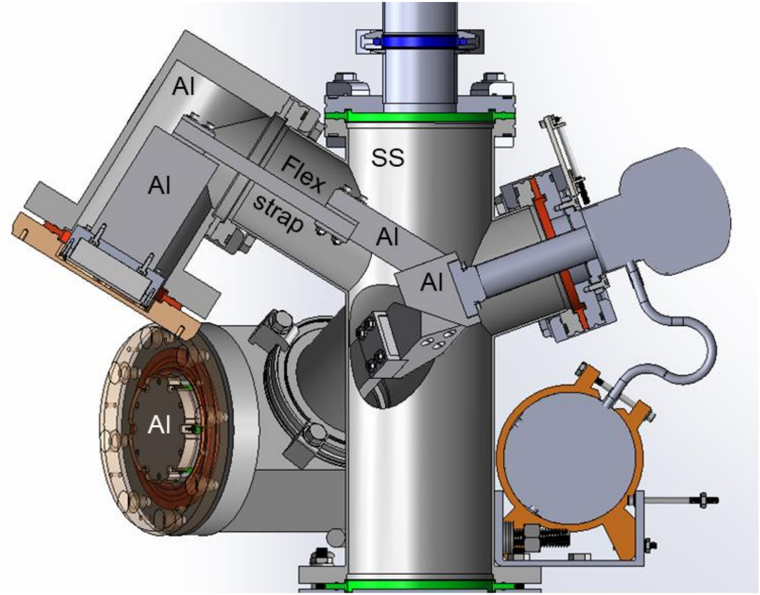


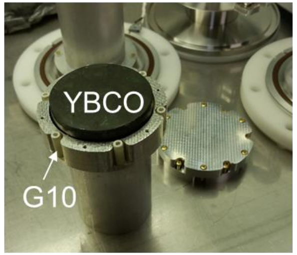


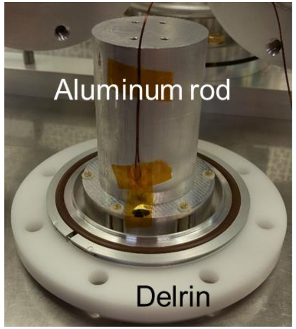
Solution

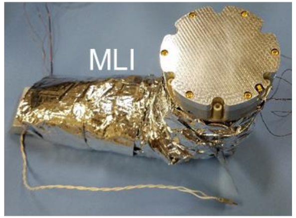
Device Description

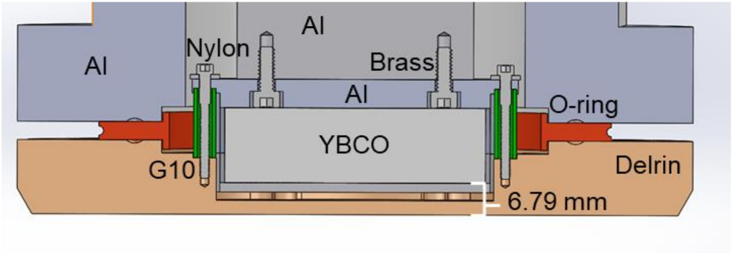
- 3x Yttrium barium copper oxide (YBCO) superconductor disks in aluminum housings
- Thermally connected to cryocooler by aluminum conduction path
    - Flexible thermal straps used for compliance
- Mechanically mounted to delrin cap with thermal isolation
- Multi-layer insulation (MLI) on cold components







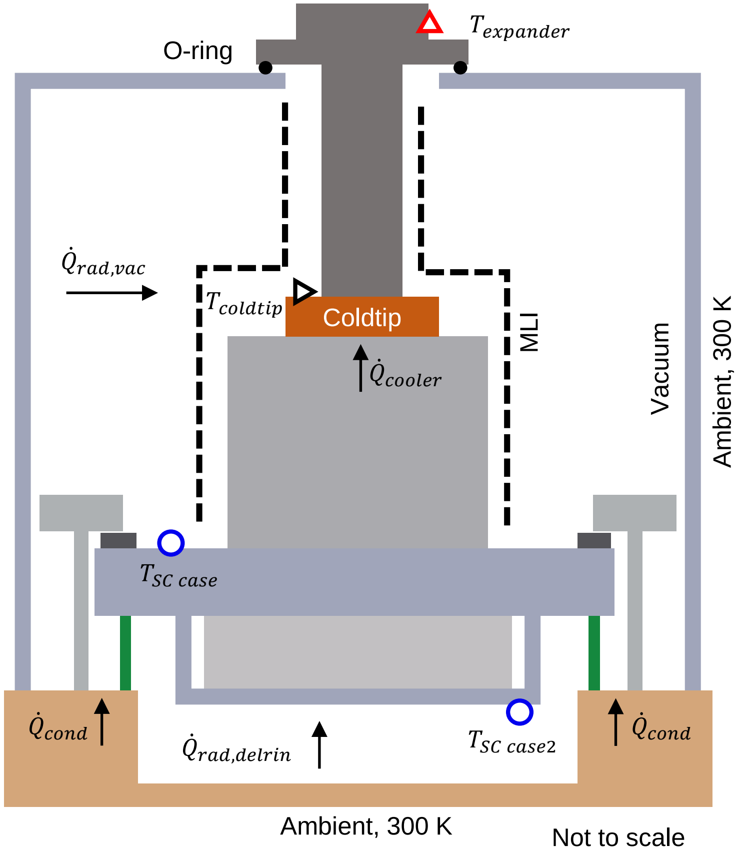




Solution

Thermal Design

- Temperature difference across superconductor case <1 K
- Conduction paths:
  - Tortuous from superconductor to delrin cap
  - Excellent from superconductor to coldtip
- Vacuum environment eliminates convective heat transfer
- Heat rejected from the cryocooler to ambient air by convection
- Radiative heat transfer from vacuum to cold components minimized with MLI

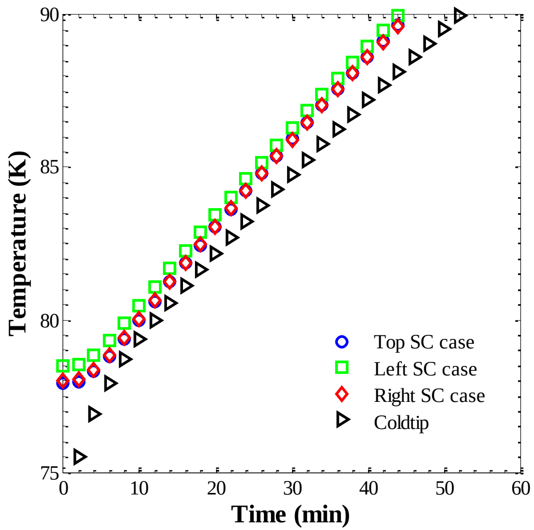


Solution

Operational Timeline

- Place/mount a permanent magnet near each delrin cap for field cooling
- Turn on vacuum pump
  - Wait ~1 hour for pressure to reach 10^{-4} torr
- Turn on cryocooler and cooling fans
  - Wait ~13 hours for superconductors to be less than 88 K
- Remove magnet mounting and observe magnet equilibrium position
- Perform dynamics experiments in testbed
  - Can operate for weeks at a time
- Turn off cryocooler
  - FPI maintained for ~30 minutes with cryocooler off
  - Warm up takes ~66 hrs without heating

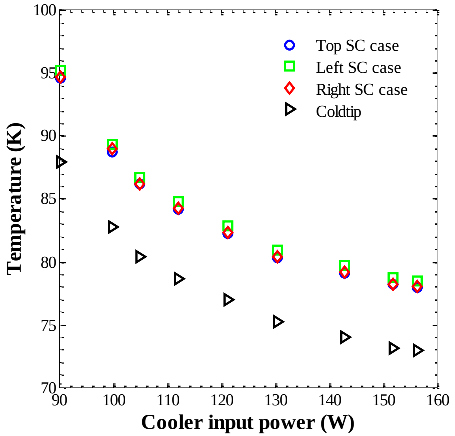
Video(s) of magnets floating

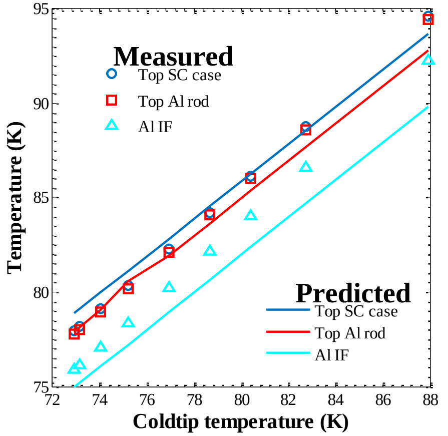


Solution

Thermal Performance and Modeling

- Device able to bring superconductors below 88 K with 105 W of cryocooler input power
- Multi-mode heat transfer: conduction and radiation
  - Difficult to solve analytically
- Thermal model created in SolidWorks 2016
  - Conduction along path from superconductor to cold tip
    - Thermal interface resistances accounted for
  - Radiation from environment to cold components
- Model temperature predictions agree with measured data
  - Predicted heat lift compares well with cryocooler performance measurements
- Model can be applied to spacecraft environment
  - To predict power consumption of cryocooler



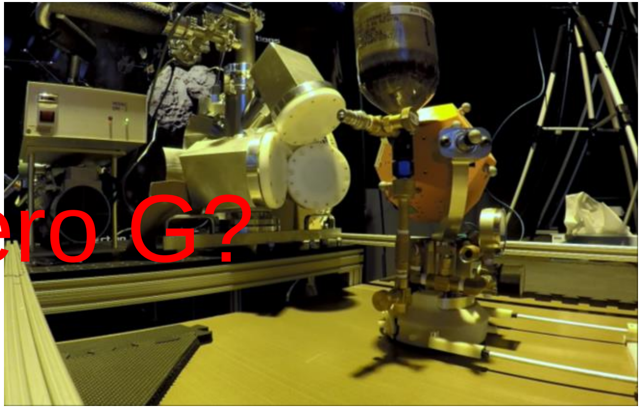


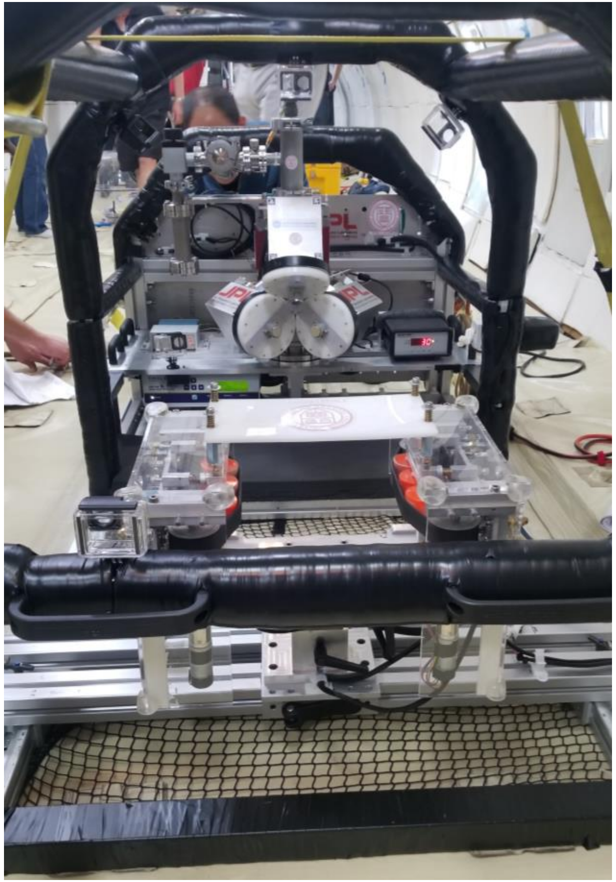
Solution

Successful Demonstration in Testbeds

- Ground with air bearing: Four degrees of freedom
    - Operated for approximately a month at a time
- Microgravity: Six degrees of freedom
    - Successfully flown on two Zero-G flight campaigns
    - Getter pump used to maintain vacuum

Video of
Flatfloor? Zero G?





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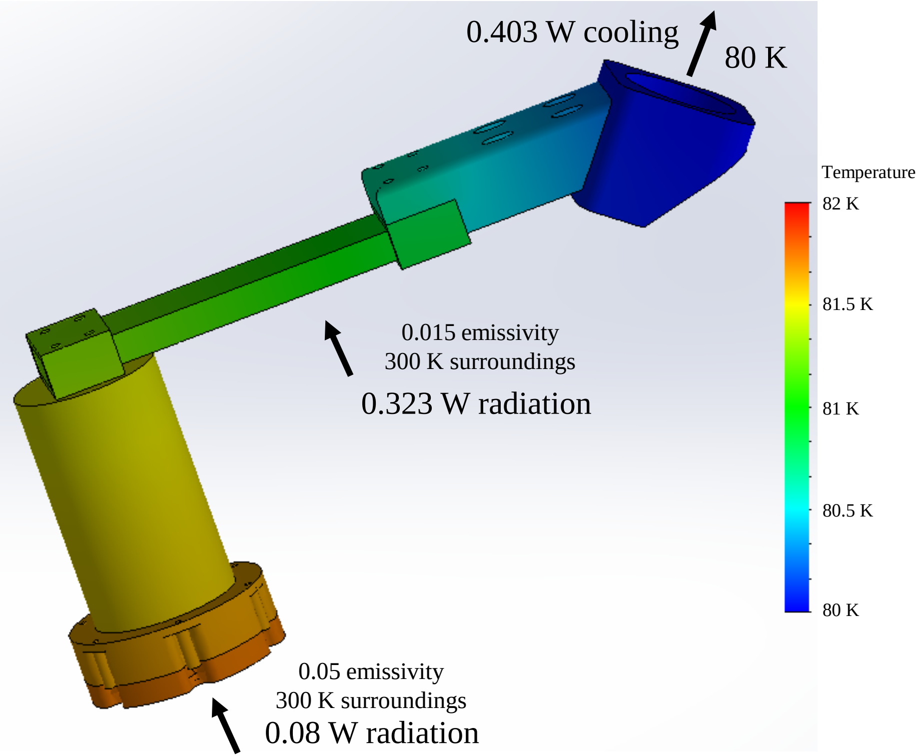
Solution

Predicting Thermal Performance in Space

- Model setup:
  - Conductive path from superconductor to cold tip same as device thermal model
  - MLI emissivity larger than device
  - Conduction to delrin cap eliminated
  - Surrounding temperature of 300 K
  - Cold tip temperature of 80 K
- 1.82 W of cooling total
  - 0.403 W per superconductor plus 50% margin for concept-definition phase
- Cryocooler consumes 57 W of power
  - 293 K heat rejection
- Superconductors at 81.65 K



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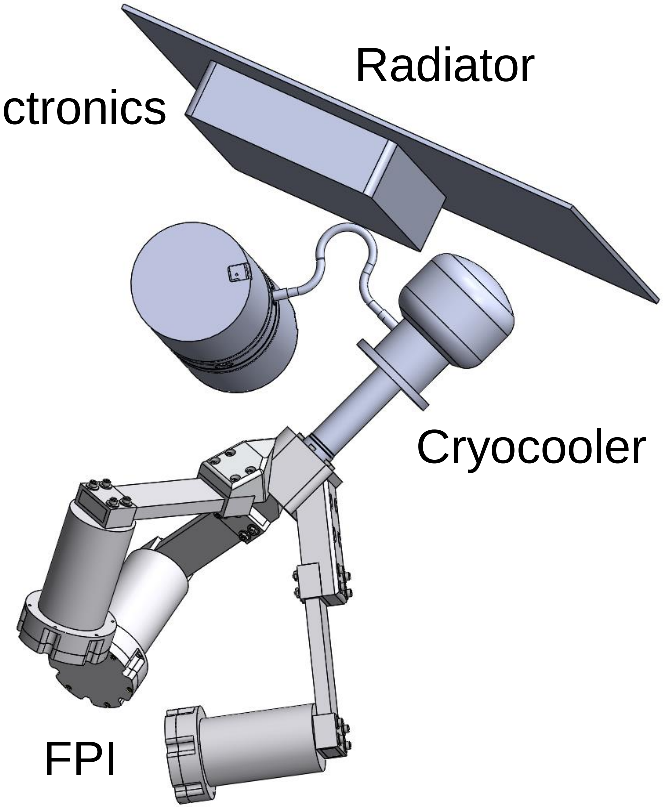
Solution

Modifying Device for Space

- Remove vacuum enclosure
- Radiator to reject 57 W of cryocooler heat
  - 0.138 m^2 at 300 K
- Flight electronics: Iris Technologies Low-cost control electronics
  - 2 kg and >85% efficiency
- Other potential changes:
  - Thermal strap from aluminum to pyrolytic graphite film
    - Reduces mass
    - Better thermal conductance
  - Reduce thermal interface resistances



Summary/ Recommendations

- Thermal subsystem successful in two different testbeds
    - Device will operate indefinitely with vacuum pump
- Thermal modeling principles were developed and model was verified
    - Model used to predict power consumption in space
- Further technology development:
    - Operate the thermal system in a larger vacuum chamber
        - Flight-like demonstration
        - Verify the model predictions without heat leak to the vacuum chamber
    - Develop cryogenic bolted thermal interfaces for predictability and repeatability
        - Non-standard cryogenic bolted thermal interfaces hard to predict
- Future applications should be wary of the superconductors mounting
    - Thermal isolation necessary
    - Knowledge of absolute location important

Thank you for your attention

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Questions?

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